

CATALYTIC COMPOSITION FOR THE AROMATIZATION OF HYDROCARBONS

The present invention regards a catalytic composition comprising gallium, at least one element chosen in the group of the lanthanides, and a zeolite of MFI, MEL or MFI/MEL structure, the crystal lattice of which is made up of silicon oxide and at least one metal oxide chosen from among aluminium oxide, boron oxide and gallium oxide. Preferably, in the catalytic compositions of the present invention a zeolite is used belonging to the MFI family characterized by crystallites which for at least 90% have a diameter smaller than 500 Å and which can form agglomerates of submicron dimensions characterized by possessing at least 30% of the extrazeolitic porosity in the region of the mesopores.

In addition, the catalytic compositions of the present invention can contain rhenium.

These catalytic compositions are useful in processes of aromatization of aliphatic hydrocarbons having from 3 to 6 carbon atoms.

The reaction of aromatization of paraffins and light olefins ( $C_2-C_5$ ) to yield mixtures of benzene, toluene, ethylbenzene and xylenes (BTEX) has for

many years been a subject of study. In 1973, the  
use was described of zeolites having an MFI  
structure (ZSM-5, ZSM-11, ZSM-21) for the  
aromatization of light hydrocarbons (both saturated  
5 and unsaturated) resulting from cracking, and from  
the production of coker gasoline or pyrolysis  
gasoline (US 3,756,942 and US 3,845,150).

US 4,175,057 and US 4,180,689 describe the  
reaction of aromatization of propane and butane in  
10 the presence of a catalyst with a base of gallium  
and an MFI zeolite. These patents were followed by  
numerous others regarding various modifications of  
this process involving modifications of the  
catalyst (US 4,795,844), of the throughput (EP  
15 252705, EP 050021 and US 4,350,835) and of the  
system of introduction of gallium (EP 120018 and EP  
184927). In particular, EP 252705 describes a  
process for producing aromatic compounds from  
feedstock containing C<sub>2</sub>-C<sub>12</sub> aliphatic hydrocarbons,  
20 using a catalyst comprising a zeolite, having a  
constraint index from 1 to 12, a preferably very  
high silica/alumina ratio, and from 0.5 to 10% of  
gallium. Possibly, other elements chosen from among  
the metals belonging to the Groups I-VIII may be  
25 present.

It has moreover been found that the addition of platinum and palladium to the Ga and MFI zeolite-based catalyst determines an improvement in the aromatic-compound selectivity and reduces the formation of coke on the catalyst (US 4,407,728 and EP 215579, 216491, 224162, 228267). The presence of these metals increases, however, the formation of methane and ethane deriving from cracking. Subsequently, it was found that the introduction of rhenium, in the presence of platinum or palladium, determines a further improvement in the aromatic-compound selectivity, but also in this case there is an increase in the amount of C<sub>1</sub>-C<sub>2</sub> light paraffins among the products (US 4,766,265).

Catalytic compositions containing copper, or chromium, and an MFI zeolite determine the formation of smaller amounts of methane, but the aromatic-compound selectivity remains smaller than the one obtained with catalytic compositions containing gallium and an MFI zeolite (P. Meriaudeau et al., Zeolites: Facts, Figures, Future, 1423-1429, 1989; E. S. Shapiro et al., International Symposium on Zeolites as Catalysts, Sorbents and Detergent Builders, Wurzburg (RFA), p.73, 1988).

Also described are catalysts containing an MFI zeolite, a noble metal of the Pt family, a metal chosen from among Sn, Ge, In and Pb, and an alkaline and/or alkaline earth component (EP 5 474536). This catalytic system involves an improvement in the aromatic-compound selectivity as compared to the foregoing materials.

All the catalytic systems described above are characterized by a very short life, since, an 10 account of the high temperatures necessary for the reaction of aromatization of olefins and light paraffins, there is an important phenomenon of fouling and formation of coke inside the pores of the catalyst. This phenomenon is linked essentially 15 to phenomena of cracking and/or of polycondensation of the compounds present in the reaction environment.

There has now been surprisingly found a catalytic system comprising gallium, at least one 20 element chosen in the group of the lanthanides and a zeolite based on silica and at least one metal oxide chosen from among alumina, boron oxide and gallium oxide, belonging to the MFI, MEL or MFI/MEL families, which, in the reaction of aromatization 25 of C<sub>3</sub>-C<sub>6</sub> light hydrocarbons, enables higher levels

of selectivity to be obtained as compared to known catalytic systems, in particular those based on gallium and MFI zeolite, and moreover presents a greater resistance to deactivation, with a  
5 consequent considerable increase in life.

A first subject of the present invention is therefore a catalytic composition comprising gallium, at least one element chosen in the group of the lanthanides and a zeolite belonging to the  
10 MFI, MEL or MFI/MEL families, the crystal lattice of which is made up of silicon oxide and at least one metal oxide chosen from among aluminium oxide, boron oxide and gallium oxide. This catalytic composition can, in addition, contain rhenium, and  
15 hence a particular aspect of the present invention is a catalytic composition comprising rhenium, gallium, at least one element chosen in the group of the lanthanides and a zeolite belonging to the MFI, MEL or MFI/MEL families, the crystal lattice  
20 of which is made up of silicon oxide and at least one metal oxide chosen from among aluminium oxide, boron oxide and gallium oxide.

The zeolite of the MFI family which is particularly suited for being used in the present  
25 invention is the zeolite ZSM-5 having a crystal

lattice based on silicon oxide and aluminium oxide, as described in US 3702886. Other zeolites of the MFI family which are particularly suited for being used in the present invention are the zeolites 5 having an MFI structure based on silicon oxide, gallium oxide, and possibly aluminium oxide, as described in EP 252705, as well as the zeolites having an MFI structure based on silicon oxide and boron oxide, as described in US 4656016.

10 In the MEL family, the zeolite which is best suited for being used in the catalytic composition of the present invention is ZSM-11, described in US 3,709,979. Other zeolites of the family MEL which are particularly suited for being used in the 15 present invention are the zeolites having an MEL structure based on silicon oxide and boron oxide, as described in J. Appl. Cryst. (1984), 17, 403-410. In the MFI/MEL family, a zeolite that can well be used is ZSM-8, described in GB 1334243. Likewise 20 usable is the zeolite having an MFI/MEL structure based on silicon oxide and boron oxide, as described in ACS Symp. Series 398, p. 361 (1989).

Forming a particularly preferred aspect of the present invention are the catalytic compositions 25 containing the ZSM-5 zeolite.

Preferably, in the catalytic composition of the present invention the zeolite is partially in acid form, i.e., part of the cationic sites present in the zeolite is occupied by hydrogen ions.

5       The molar ratio in the crystal lattice of the zeolite between silicon oxide and metal oxide, where the metal oxide is chosen from among aluminium oxide, boron oxide and gallium oxide or their mixtures, is preferably greater than 20. A  
10 preferred aspect is that said ratio is greater than 20 and less than 500, preferably, greater than 20 and less than 400. An even more preferred aspect is that said ratio is greater than 20 and less than 200, preferably, greater than 20 and less than 100.  
15      A still more preferred aspect is that said ratio is greater than 20 and less than or equal to 70, preferably, greater than 20 and less than 60.

It has, in particular, been found that using, in the catalytic system of the present invention,  
20     an MFI zeolite characterized by an appropriate size of the crystallites, in the reaction of aromatization of C<sub>3</sub>-C<sub>6</sub> light hydrocarbons, particularly high yields are obtained as compared to the known catalytic systems, with a greater  
25     percentage, in the fraction of the by-products, of

recoverable products. Moreover, this catalytic system containing an MFI zeolite with sizes of the crystallites appropriately selected presents greater resistance to deactivation, with a 5 consequent considerable increase in life.

A particular subject of the present invention is consequently a catalytic composition comprising gallium, at least one element chosen in the group of the lanthanides and a zeolite belonging to the 10 MFI family characterized by crystallites which for at least 90% have diameters smaller than 500 Å. Preferably, the zeolite is partially in acid form.

Also this particular catalytic composition can, in addition, contain rhenium. The crystallites 15 of the MFI zeolite used in this particular aspect of the present invention can present in the form of submicron mulberry-shaped aggregates with an extrazeolitic porosity of a meso-macroporous nature. By "extrazeolitic porosity" is meant the 20 porosity obtained by summing the fraction of mesoporosity and macroporosity (determined by means of mercury-intrusion porosimetry up to a pressure of 2000 bar) present in the aggregate, hence excluding the contribution of the microporosity of 25 the zeolite. The total volume of said extrazeolitic

porosity is constituted for at least 30% by mesopores (diameter < 500 Å). Preferably, in said catalytic compositions MFI zeolites are used consisting of crystallites with a diameter of less than 500 Å.

The zeolite of the MFI family having for at least 90% diameters of less than 500 Å which is very suitable for being used in this particular aspect of the invention is an MFI zeolite the crystal lattice of which is made up of silicon oxide and aluminium oxide (ZSM-5). A preferred aspect is that the molar ratio between the silicon oxide and aluminium oxide in the crystal lattice of said zeolite is greater than 20.

Preferably, said molar ratio is greater than 20 and less than 500, preferably, less than 400. An even more preferred aspect is that said ratio is greater than 20 and less than 200, preferably, greater than 20 and less than or equal to 100.

A process that can well be used for preparing this MFI zeolite having crystallites which for at least 90% have diameters smaller than 500 Å is described in US 3926782. According to the method described in this patent, the MFI zeolites with crystallites of diameters for at least 90% smaller

than 500 Å, usable in the catalytic compositions of the present invention, are prepared using a solution containing sources of tetra-propyl-ammonium ion, sodium oxide, aluminium oxide, silicon oxide, and water, having the following composition expressed as molar ratios:

$$\begin{aligned}\text{OH}^{-\text{free}}/\text{SiO}_2 &: 0.07-1.0 \\ (\text{C}_3\text{H}_7)_4\text{N}^+/\text{SiO}_2 &: 0.01-1 \\ \text{H}_2\text{O}/\text{OH}^{-\text{free}} &: 10-300 \\ 10 \quad \text{SiO}_2/\text{Al}_2\text{O}_3 &: > 5 \\ \text{Na}^+/\text{SiO}_2 &: 0.6-5\end{aligned}$$

where by  $\text{OH}^{-\text{free}}$  are meant the  $\text{OH}^-$  ions not neutralized by  $\text{H}^+$  ions added to the reaction mixture directly, for example by means of acid compounds, or indirectly, for example using  $\text{Al}(\text{NO}_3)_3$  or  $\text{Al}_2(\text{SO}_4)_3$ .

Preferably, the composition of the synthesis mixture is the following:

$$\begin{aligned}20 \quad \text{OH}^{-\text{free}}/\text{SiO}_2 &: 0.1-0.3 \\ (\text{C}_3\text{H}_7)_4\text{N}^+/\text{SiO}_2 &: 0.05-0.25 \\ \text{H}_2\text{O}/\text{OH}^{-\text{free}} &: 20-60 \\ \text{SiO}_2/\text{Al}_2\text{O}_3 &: 50-120 \\ \text{Na}^+/\text{SiO}_2 &: 1-4\end{aligned}$$

To obtain MFI zeolites having crystallites 25 with diameters that for at least 90% are less than

500 Å, a high rate of stirring is required, and preferably the peripheral rate must be between 20 and 200 m/min. The conditions in which crystallization is conducted comprise a temperature 5 in the range of from 90 to 130°C, under stirring for a time interval which ranges from 3 hours to 15 days, possibly followed by a second stage which can last up to 5 days in which the temperature is raised to a value ranging from 110 to 160°C to 10 accelerate completion of crystallization.

The source of tetra-propyl-ammonium ion can be the corresponding hydroxide or bromide, or tri-*n*-propylamine in a mixture with *n*-propyl bromide, dissolved in an appropriate solvent, such as 15 methyl-ethyl-ketone.

The sources of silicon oxide comprise sodium silicate, silica hydrosol, silica gel and silicic acid. The source of aluminium oxide can be chosen from among sodium aluminate, alumina, aluminium salts, such as aluminium sulphate or aluminium 20 nitrate.

The source of sodium can be chosen from among salts of sodium such as hydroxide, halides and/or sulphate. In addition or as an alternative, the 25 sodium may be derived from the sources of aluminium

and/or silicon which contain it.

To obtain the desired concentration of free OH<sup>-</sup> ions, mineral acid reagents, such as sulphuric acid or nitric acid can be added to the mixture.

5 The reagents can be mixed together in any order, crystallization is preferably conducted in autoclave.

In the catalytic compositions of the present invention, the element belonging to the group of 10 the lanthanides that is preferably used is chosen from among neodymium and lanthanum, alone or in mixture with cerium and/or praseodymium. An even more preferred aspect is that the present invention uses mixtures of neodymium and lanthanum, possibly 15 also containing cerium and/or praseodymium.

The lanthanide, or lanthanides, present in the catalytic composition according to the invention can be in the form of oxide, ion or metal, or can be present in a mixture of these forms. The amount 20 of lanthanide, or lanthanides, expressed as element, can range from 0.01 to 10 wt%, preferably from 0.1 to 2 wt%, with respect to the total weight of the catalytic composition.

The gallium present in the catalytic 25 composition can be in the form of oxide, gallium

ion or metallic gallium, or can be a mixture of said forms. The amount of gallium, expressed as element, can range from 0.05 to 10 wt% with respect to the total weight of the catalytic composition,  
5 and is preferably from 0.5 to 4 wt%.

The gallium and the lanthanide can be introduced in the catalytic composition in any order, treating the zeolite, preferably in acid form, with a gallium compound and a lanthanide  
10 compound, or else, using a mixture containing both a gallium compound and a lanthanide compound, it is possible to introduce both the elements in the catalytic composition simultaneously.

When the catalytic composition of the present  
15 invention contains more than one lanthanide in its preparation, a mixture of compounds of these lanthanides will be used.

The best results in terms of catalytic activity are obtained when the catalytic composition is prepared by first introducing the gallium and then the lanthanide.  
20

To introduce the gallium, any one of the known techniques can be used, such as mechanical mixing with gallium oxide, ion exchange or impregnation.  
25 Preferably, ion exchange or impregnation is used.

In the first case, the zeolite is treated, preferably, in acid form, with an aqueous solution of a gallium salt having a concentration which can range from 0.01 to 0.5 M, for example a solution of gallium nitrate, gallium chloride or gallium sulphate, refluxed for 1-24 hours.

The specimen resulting from ion exchange, after appropriate washings with demineralized water, is dried at 100-150°C and then calcined at a temperature ranging from 400 to 600°C for 1-10 hours.

In the case where it is chosen to introduce the gallium using the impregnation technique, the zeolite is treated with the aqueous solution of a gallium salt, proceeding according to the known art of wet imbibition. This is followed by drying and calcining as in the case of ion exchange.

The stage of calcining determines at least partial transformation of the gallium ion into the corresponding oxide.

Ion exchange or impregnation are the techniques which are preferably used to introduce the gallium.

In the zeolite containing gallium, prepared in the foregoing stage with one of the techniques

described above, the lanthanide can be introduced by means of the known techniques of mechanical mixing with an oxide of a lanthanide, impregnation or ion exchange. The techniques of ion exchange or  
5 impregnation are preferably used. In the former case, the composition containing the zeolite and the gallium is treated with an aqueous solution of a salt of the lanthanide, for example an aqueous solution of the corresponding nitrate, acetate,  
10 chloride or sulphate with a concentration of 0.01-0.5 M, refluxed for 1-24 hours. The specimen resulting from ion exchange, after appropriate washings, is dried and then calcined at a temperature ranging from 400 to 600°C for 1-10  
15 hours.

In the case where the lanthanide is introduced by impregnation, the procedure is according to the known art of wet imbibition. This is followed by drying and calcining as in the case of ion  
20 exchange.

On account of calcining, there will be an at least partial transformation of the lanthanide ion into the corresponding oxide.

Impregnation is the technique which is  
25 preferably used to introduce the lanthanide.

The two foregoing stages of introduction of the gallium and of the lanthanide can be carried out inverting the sequence and introducing the lanthanide before the gallium.

5        Whatever the sequence chosen, the calcining between the stage of introduction of the first metal and the stage of introduction of the second metal is optional; in the case where calcining was not carried out, the partial transformation of the 10 metal ions into the corresponding oxides will take place simultaneously during calcining performed at the end of the second stage.

According to a particularly preferred aspect, the catalytic compositions of the present invention 15 are prepared by depositing the gallium on the zeolite in acid form by means of ion exchange or impregnation, possibly calcining the product thus obtained, then depositing the lanthanide by impregnation and calcining the product obtained.

20       This may be followed by a stage of at least partial reduction of the lanthanide ion and of the gallium ion to the corresponding metals. The reduction to metal may be obtained by means of treatment of the catalytic composition with 25 hydrogen or with a reducing agent, and can be

performed on the catalytic composition before its use, or else in the reactor itself in which the catalytic composition will be used.

When the catalytic compositions of the present invention also contain rhenium, this can be in the form of oxide, ion or metal, or can be a mixture of said forms. The amount of rhenium, expressed as element, can range from 0.05 to 10 wt% with respect to the total weight of the catalytic composition, 10 and preferably is from 0.5 to 4 wt%.

The rhenium can be introduced in any order into the catalytic composition with respect to the introduction of gallium and lanthanide, or else a mixture which contains all three elements can be 15 used.

To introduce the rhenium any of the known techniques can be used, such as mechanical mixing with rhenium oxide, ion exchange or impregnation. Preferably, ion exchange or impregnation is used, 20 performed with the techniques already previously described. Impregnation is the method which is preferably used, performed, for example, with an aqueous solution of rhenium chloride having a concentration of 0.01-0.5 M, applying the known art 25 of wet imbibition. The product is then dried and

calcined. During calcining, there is the at least partial transformation of the rhenium ion in the corresponding oxide.

A particularly preferred aspect is to  
5 introduce the rhenium into the catalytic composition after introducing the gallium and the lanthanide, i.e., treating the zeolite by means of ion exchange or impregnation with an aqueous solution of a gallium salt, drying, possibly  
10 calcining the resulting product, and then treating it by means of impregnation with an aqueous solution of lanthanide, drying it, possibly calcining it, and finally treating the resulting product with an aqueous solution of a rhenium salt,  
15 drying and calcining. A stage of reduction performed after introduction of the rhenium ion will result in the at least partial transformation of this ion into metallic rhenium.

The catalytic composition of the present  
20 invention can be used in mixture with appropriate binders, such as silica, alumina, and clay. The catalytic composition and the binder are mixed in a proportion ranging from 50:50 to 95:5, preferably from 60:40 to 90:10. The mixture of the two  
25 components is processed to obtain the desired final

form, for example as cylindrical or spheroidal extrudate, or other known forms.

The catalytic compositions described above are useful in processes for the production of aromatic hydrocarbon compounds from light aliphatic hydrocarbons.

A further subject of the present invention is therefore a process for the production of aromatic hydrocarbon compounds, which comprises setting in contact one or more aliphatic hydrocarbons containing from 3 to 6 carbon atoms with a catalytic composition comprising gallium, at least one element chosen in the group of the lanthanides and a zeolite belonging to the MFI, MEL or MFI/MEL families, having a crystal lattice made up of silicon oxide and at least one oxide chosen from among aluminium oxide, boron oxide and gallium oxide.

A preferred aspect of the aromatization process according to the present invention uses a zeolite in the partially acid form. Among the zeolites that may be used, the zeolite ZSM-5 is preferred. The molar ratio in the crystal lattice of the zeolite between silicon oxide and metal oxide, where the metal oxide is chosen from among

aluminium oxide, gallium oxide or their mixtures, is preferably greater than 20. A preferred aspect of the present invention is that said ratio is greater than 20 and smaller than 500, preferably 5 smaller than 400. An even more preferred aspect is that said ratio is greater than 20 and less than 200, and still more preferably smaller than 100.

The best results are obtained when said ratio is greater than 20 and less than or equal to 70, 10 preferably less than 60.

A particular aspect of the aromatization process of the present invention uses the catalytic compositions which additionally contain a rhenium ion, and hence a particular aspect of the present 15 invention is a process for the production of aromatic hydrocarbon compounds which comprises setting in contact one or more aliphatic hydrocarbons containing from 3 to 6 carbon atoms with a catalytic composition comprising gallium, at least one element chosen in the group of the lanthanides and a zeolite belonging to the MFI, MEL 20 or MFI/MEL families, having a crystal lattice made up of silicon oxide and at least one oxide chosen from among aluminium oxide, boron oxide and gallium 25 oxide.

A further particular subject of the present invention is a process for the production of aromatic hydrocarbon compounds which comprises setting in contact one or more aliphatic 5 hydrocarbons containing from 3 to 6 carbon atoms with a catalytic composition comprising gallium, at least one element chosen in the group of the lanthanides and a zeolite belonging to the MFI family characterized by crystallites which for at 10 least 90% have diameters smaller than 500 Å. The zeolite is preferably in a partially acid form.

This catalytic composition can in addition contain rhenium.

Preferably, MFI zeolites are used consisting 15 of crystallites having diameters of less than 500 Å. A particularly preferred aspect is to use MFI zeolites having for at least 90% diameters of less than 500 Å, the crystal lattice of which is made up of silicon oxide and aluminium oxide. Preferably, 20 the molar ratio between silicon oxide and aluminium oxide in the crystal lattice of the said zeolite is greater than 20. A preferred aspect of the present invention is that said ratio is greater than 20 and smaller than 500, preferably smaller than 400. An 25 even more preferred aspect is that said ratio is

greater than 20 and less than 200, still more preferably, less than or equal to 100.

Preferred catalytic compositions are those containing neodymium or lanthanum, either alone or 5 in mixture with cerium and/or praseodymium. An additional preferred aspect of the present invention is to use mixtures of neodymium and lanthanum, possibly also containing cerium and/or praseodymium.

10 In the aromatization process of the present invention, as aliphatic hydrocarbons containing from 3 to 6 carbon atoms, paraffins, olefins, cycloparaffins, cyclo-olefins or their mixtures may well be used. Preferably, aliphatic hydrocarbons 15 containing from 4 to 5 carbon atoms are used.

Examples of aliphatic hydrocarbons that can well be used in the process of the present invention are *n*-pentane, *n*-pentenes, *n*-butane, *n*-butenes, iso-butane, iso-butene, methylbutenes, 20 cyclopentenes, isopentane, cyclopentane, or their mixtures.

According to a preferred aspect of the invention, mixtures of hydrocarbons containing from 20 to 90 wt%, preferably from 40 to 70 wt%, of 25 olefins, are used.

The aliphatic hydrocarbons having from 3 to 6 carbon atoms used in the process of the present invention can derive from steam cracking, FCC (fluid catalytic cracking) and thermal cracking, by means of the known methods of separation and distillation, and can contain smaller amounts of other types of hydrocarbons, such as aromatic hydrocarbons. They may also contain dienes (either linear or cyclic) in an amount not higher than 5 wt%. When this percentage of dienes is higher than 5 wt%, the charge of aliphatic hydrocarbons is subjected to a treatment of selective hydrogenation according to known methods, for example with a palladium-based catalyst, so as to bring the percentage of dienes to a value smaller than 5 wt%.

The process of the present invention is conducted at a temperature of between 300° and 800° C, preferably between 400° and 650°C, at a pressure of from 0 to 20 barg, preferably from 1 to 10 barg. The process is preferably conducted continuously, in a fixed-bed or fluidized-bed reactor, in the gas phase or partially liquid phase, at a weight hourly space velocity (WHSV, expressed as grams of feedstock / (grams of catalyst . hour)) ranging from 0.1 to 30 hours<sup>-1</sup>, preferably from 0.5 to

10 hours<sup>-1</sup>.

Hydrogen or inert gas (nitrogen) can be introduced in the reaction system as diluent.

Before the catalytic composition of the present invention is used, it was activated in nitrogen at a temperature ranging from 300 to 800°C, preferably from 300 to 700°C, for a period of between 1 and 24 hours, and at a pressure of between 0 and 10 barg.

In addition to or as a substitution for the foregoing procedure, activation with hydrogen can be performed at a temperature of 300-700°C, a pressure of 0-10 barg, for a period of between 1 and 24 hours.

15           Example 1

Preparation of Ga-ZSM-5

25 g of a commercially available ZSM-5 zeolite (PQ Zeolites, CBV 3020), having a SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio of 30 and already exchanged into acid form, was treated with 470 ml of an aqueous solution of Ga(NO<sub>3</sub>)<sub>3</sub>.9H<sub>2</sub>O (0.02 M). Ion exchange was conducted under stirring and reflux for 2 hours. The catalyst was subsequently filtered, washed with distilled water, filtered again, and dried in air at 120°C. Finally it was calcined in air at 550°C for 5

hours. The final content of Ga was 2 wt%. The specimen is referred to as Ga-ZSM-5.

Example 2

Preparation of GaNd (0.4)-ZSM-5

5 A catalyst having a final content of neodymium of 0.4 wt% was prepared starting from 8 g of the foregoing specimen of Example 1 (Ga-ZSM-5) by means of impregnation with 10 ml of an aqueous solution of  $\text{Nd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$  (0.020 M). The catalyst was  
10 subsequently dried at 120°C and calcined in air at 550°C for 5 hours. The specimen is referred to as GaNd (0.4)-ZSM-5.

Example 3

Preparation of GaNd (1.0)-ZSM-5

15 The catalyst having a final content of neodymium of 1 wt% was prepared starting from 8 g of the Ga-ZSM-5 specimen of Example 1 by means of impregnation with 10 ml of an aqueous solution of  $\text{Nd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$  (0.045 M). The catalyst was  
20 subsequently dried at 120°C and calcined in air at 550°C for 5 hours. The specimen is referred to as GaNd (1.0)-ZSM-5.

Example 4

Preparation of Ga(i)Nd (0.4)-ZSM-5

25 The catalyst Ga(i)Nd (0.4)-ZSM-5 (with a final

content of Nd of 0.4 wt%) was prepared starting from 8 g of a commercially available ZSM-5 zeolite (PQ Zeolites, CBV 3020), having a  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of 30 and already exchanged into acid form, by means of impregnation with an aqueous solution first of  $\text{Ga}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$  (7.5 ml, 0.32 M), and then of  $\text{Nd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$  (10 ml, 0.020 M). Between the two impregnations, the catalyst was subjected to drying (in air at  $120^\circ\text{C}$ ). At the end of the operations, the specimen was subsequently dried at  $120^\circ\text{C}$  and calcined in air at  $550^\circ\text{C}$  for 5 hours. The specimen is referred to as Ga(i)Nd (0.4)-ZSM-5.

Example 5

Preparation of Nd-ZSM-5

15 The Nd-ZSM-5 specimen was prepared by impregnation of 8 g of a commercially available ZSM-5 zeolite (PQ Zeolites, CBV 3020), having a  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio of 30 and already exchanged into acid form, by means of 10 ml of an aqueous solution 20 of  $\text{Nd}(\text{NO}_3)_3$  (0.020 M). The catalyst was subsequently dried at  $120^\circ\text{C}$  and finally calcined in air at  $550^\circ\text{C}$  for 5 hours. The final content of Nd was 0.4 wt%. The specimen is referred to as Nd-ZSM-5.

25 Example 6

Aromatization test of 1-pentene / n-pentane  
with HZSM-5 (comparative)

An aromatization test of a charge of C<sub>5</sub> hydrocarbons (made up of 1-pentene and n-pentane) in a weight ratio of 40:60 was conducted using an experimental apparatus consisting of a steel reactor (length = 710 mm, internal diameter = 12.5 mm, external diameter = 35 mm) equipped with an internal thermometric sheath for control of the temperature. Heating took place with the aid of 4 ovens arranged in series along the reactor itself. The catalyst was introduced in the form of granules of appropriate sizes (20-40 mesh) and diluted with inert material. The feeding of the reagents (contained in a special refrigerated tank and kept under pressure in nitrogen) was performed using an HPLC pump. The products coming out of the reactor were condensed (at a temperature of 5 °C) and collected, partly in the liquid phase, and partly in the gas phase. Both the phases then underwent gas-chromatography analysis.

The catalyst used in this test was a commercially available ZSM-5 zeolite in acid form (commercial specimen PQ CBV 3020) having a SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio of 30.

The reaction conditions during the test were  
the following:

Reaction temperature : 350-400°C

Pressure : 5 barg

5 WHSV : 5 g/g/hr

[1-pentene]/[n-pentane] : 40:60 w/w

3 g of catalyst were introduced in the reactor  
(the catalyst being obtained by tabletting the  
powdered ZSM-5 zeolite at a pressure of 10 ton/cm<sup>2</sup>,  
10 and by grinding it and sifting it in granules  
having a size of 20-40 mesh) between two layers of  
inert material (corindone). The catalytic bed had a  
depth of 3-4 cm. Before the reaction, the material  
was activated in a current of nitrogen at 400°C for  
15 3-4 hours.

Table 1 gives the results of the test. In this  
table and in the tables of the ensuing examples of  
activity, the results are expressed in terms of  
conversion of the 1-pentene, value of the  
20 conversion of the n-pentane, final content by  
weight of BTEX product (benzene, toluene,  
ethylbenzene and xylene), of aromatic compounds  
(where C<sub>6</sub>-C<sub>10</sub> benzene aromatic compounds are meant),  
of olefins (where all the olefins are meant, with  
25 the exclusion of non-reacted 1-pentene), of

paraffins (where all the paraffins are meant, with the exclusion of non-reacted *n*-pentane) and of naphthalenes ( $C_{10}-C_{13}$ ). Finally, the overall value of BTEX productivity is given (obtained from the 5 start of the test up to value of time on stream of the corresponding sampling) calculated as:

BTEX productivity = kg BTEX produced / kg of catalyst

**Table 1**

Time on stream (hours)	4.5	7.5	17.5
Temperature ( $^{\circ}C$ )	400	350	350
Conversion of 1-pentene (%)	99.9	99.9	99.9
Conversion of pentane (%)	98.5	88.2	36.8
BTEX (wt % over total)	15.2	10.7	8.4
Total aromatic compounds (wt %)	18.4	15.9	13.4
Total olefins (wt%)	0.4	0.6	1.6
Total paraffins (wt%)	75.9	73.4	44.4
Total naphthalenes (wt%)	2.9	1.3	0.3
BTEX productivity (kg/kg)	2.9	4.2	8.2

10

Example 7

Aromatization test of 1-pentene/*n*-pentane with  
Ga-ZSM-5 (comparative)

The aromatization test was conducted according

to same procedure as indicated in Example 6.

The catalyst used in this test was the Ga-ZSM-5 zeolite prepared as indicated in Example 1.

The reaction conditions during the test were 5 the following:

Reaction temperature : 400-500°C

Pressure : 5 barg

WHSV : 10 g/g/hr

[1-pentene]/[n-pentane] : 40:60 w/w

10 2 g of catalyst were introduced in the reactor (the catalyst being obtained by tabletting the powdered Ga-ZSM-5 zeolite of Example 1 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and sifting it in granules having a size of 20-40 mesh)

15 between two layers of inert material (corindone). The catalytic bed had a depth of 2-3 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

Table 2 gives the results of the test,  
20 expressed in a similar way as in Table 1.

**Table 2**

Time on stream (hours)	4.5	9.5	14.0	21.5	25.5
Temperature (°C)	400	400	400	500	500

Conversion of 1-pentene (%)	99.9	99.9	99.9	99.9	98.6
Conversion of pentane (%)	97.6	87.9	52.2	57.0	0.0
BTEX (wt% over total)	16.8	14.2	11.8	14.6	3.3
Total aromatic compounds (wt%)	21.1	18.9	17.1	17.3	4.9
Total olefins (wt%)	0.4	1.3	2.6	9.4	19.2
Total paraffins (wt%)	75.3	70.7	49.4	43.5	10.3
Total naphthalenes (wt%)	0.7	0.3	0.4	2.76	0.3
BTEX productivity (kg/kg)	7.6	15.1	20.9	29.2	31.3

Example 8 (comparative)

Aromatization test of 1-pentene/n-pentane with

Nd-ZSM-5

The aromatization test was conducted according  
5 to same procedure as indicated in Example 6.

The catalyst used in this test was the Nd-ZSM-  
5 zeolite prepared as indicated in Example 5.

The reaction conditions during the test were  
the following:

10 Reaction temperature : 400-500°C

Pressure : 5 barg

WHSV : 10 g/g/hr

[1-pentene]/[n-pentane] : 40:60 w/w

2 g of catalyst were introduced in the reactor

(the catalyst being obtained by tabletting the powdered Nd-ZSM-5 zeolite of Example 3 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and sifting it in granules having a size of 20-40 mesh) between two layers of inert material (corindone). The catalytic bed had a depth of 2-3 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

Table 3 gives the results of the test,  
expressed in a similar way as in Table 1.

**Table 3**

Time on stream (hours)	5.5	9.0	17.2
Temperature (°C)	400	400	500
Conversion of 1-pentene (%)	99.9	99.9	92.1
Conversion of pentane (%)	95.3	73.3	13.3
BTEX (wt% over total)	15.0	13.1	2.6
Total aromatic compounds (wt%)	19.0	18.8	3.4
Total olefins (wt%)	0.8	1.4	24.9
Total paraffins (wt%)	69.8	60.5	13.2
Total naphthalenes (wt%)	0.4	1.1	2.8
BTEX productivity (kg/kg)	7.5	12.8	18.0

In contrast to the foregoing comparative

catalysts, the catalyst which contained neodymium alone revealed a loss of activity at 500°C, at lower time-on-steam values. The comparative catalyst that presented the best BTEX yields was 5 the one containing gallium alone, whereas the catalyst containing neodymium alone had the worst yields, above all at 500°C, as well as a rapid decay.

*Example 9*

10           Aromatization test of 1-pentene/n-pentane with  
          GaNd (0.4)-ZSM-5

The aromatization test was conducted according to same procedure as indicated in Example 6.

The catalyst used in this test was the  
15 GaNd(0.4)-ZSM-5 zeolite prepared as indicated in  
Example 2.

The reaction conditions during the test were the following:

Reaction temperature : 400-500°C

20 Pressure : 5 barg

WHSV : 10 g/g/hr

[1-pentene] / [n-pentane] : 40:60 w/w

2 g of catalyst were introduced in the reactor  
(the catalyst being obtained by tabletting the  
powdered GaNd(0.4)-ZSM-5 zeolite of Example 2 at a

pressure of 10 ton/cm<sup>2</sup>, and by grinding it and sifting it in granules having a size of 20-40 mesh) between two layers of inert material (corindone). The catalytic bed had a depth of 2-3 cm. Before the 5 reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

Table 4 gives the results of the test, expressed in a similar way as in Table 1.

**Table 4**

Time on stream (hours)	5.5	9.0	17.2	31.2	36.2
Temperature (°C)	400	400	400	500	500
Conversion of 1-pentene (%)	99.9	99.9	99.9	99.9	99.9
Conversion of pentane (%)	92.7	86.5	72.5	84.8	48.3
BTEX (wt% over total)	17.7	16.2	14.1	21.8	14.4
Total aromatic compounds (wt%)	22.8	21.5	18.8	25.1	17.6
Total olefins (wt%)	0.6	0.7	1.3	3.7	8.5
Total paraffins (wt%)	69.9	66.5	60.0	59.2	40.7
Total naphthalenes (wt%)	0.7	1.3	1.4	1.5	0.8
BTEX productivity (kg/kg)	8.7	14.1	25.2	40.7	48.4

10 As compared to the foregoing comparative catalysts, the catalyst of the present invention revealed better BTEX yield values both at 400°C and at 500°C, as well as long performance life over

time.

Example 10

Aromatization test of 1-pentene/n-pentane with  
GaNd (1.0)-ZSM-5

5       The aromatization test was conducted according to same procedure as indicated in Example 6.

      The catalyst used in this test was the GaNd(1.0)-ZSM-5 zeolite prepared as indicated in Example 3.

10      The reaction conditions during the test were the following:

      Reaction temperature : 400-500°C

      Pressure : 5 barg

      WHSV : 10 g/g/hr

15      [1-pentene]/[n-pentane] : 40:60 w/w

      2 g of catalyst were introduced in the reactor (the catalyst being obtained by tabletting the powdered GaNd(1.0)-ZSM-5 zeolite of Example 3 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and 20 sifting it in granules having a size of 20-40 mesh) between two layers of inert material (corindone). The catalytic bed had a depth of 2-3 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

25      Table 5 gives the results of the test,

expressed in a similar way as in Table 1.

Table 5

Time on stream (hours)	5.5	9.0	17.2	24.2	31.2
Temperature (°C)	400	400	400	500	500
Conversion of 1-pentene (%)	99.9	99.9	99.9	99.9	99.9
Conversion of pentane (%)	92.8	87.6	46.9	88.2	36.0
BTEX (wt% over total)	15.4	16.9	11.0	23.2	15.2
Total aromatic compounds (wt%)	19.5	22.2	15.1	25.6	18.1
Total olefins (wt%)	2.2	1.0	1.6	2.5	5.0
Total paraffins (wt%)	68.9	65.9	49.0	62.0	35.2
Total naphthalenes (wt%)	1.3	1.5	0.7	1.3	1.1
BTEX productivity (kg/kg)	7.8	13.1	23.1	31.1	42.7

Example 11

Aromatization test of 1-pentene/n-pentane with

5 GaNd (0.4)-ZSM-5

The aromatization test was conducted according to same procedure as indicated in Example 6.

The catalyst used in this test was the GaNd(0.4)-ZSM-5 zeolite prepared as indicated in

10 Example 2.

The reaction conditions during the test were the following:

Reaction temperature : 350-475 °C

Pressure : 5 barg

WHSV : 1-2 g/g/hr

[1-pentene]/[n-pentane] : 40:60 w/w

3 g of catalyst were introduced in the reactor  
(the catalyst being obtained by tabletting the  
5 powdered GaNd(0.4)-ZSM-5 zeolite of Example 2 at a  
pressure of 10 ton/cm<sup>2</sup>, and by grinding it and  
sifting it in granules having a size of 20-40 mesh)  
between two layers of inert material (corindone).  
The catalytic bed had a depth of 3-4 cm. Before the  
10 reaction, the material was activated in a current  
of nitrogen at 400°C for 3-4 hours.

Table 6 gives the results of the test,  
expressed in a similar way as in Table 1.

Table 6

Time on stream (hours)	17.5	41.5	69.5	93.5	136.5	177.5	185
WHSV (hours <sup>-1</sup> )	2	1	1	1	1	1	1
Temperature (°C)	350	350	375	400	425	450	475
Conversion of 1-pentene (%)	99.9	99.9	99.9	99.9	99.9	99.9	99.9
Conversion of pentane (%)	85.4	72.0	81.4	90.7	91.5	88.0	75.3
BTEX (wt% over total)	13.1	16.5	20.5	21.8	28.9	25.6	24.6
Total aromatic compounds (wt%)	19.6	25.5	28.4	29.1	36.9	31.9	29.4

Total olefins (wt%)	0.7	1.2	1.2	1.1	1.4	2.6	3.3
Total paraffins (weight%)	68.1	47.9	54.6	57.4	48.2	53.3	48.9
Total naphthalenes (weight%)	0.4	3.3	1.2	2.6	3.9	1.8	1.2
BTEX productivity (kg/kg)	5.3	10.5	16.8	23.3	34.6	47.3	49.6

Example 12

Aromatization test of 1-pentene/n-pentane with  
GaNd (0.4)-ZSM-5 (1-pentene 60 wt%)

The aromatization test was conducted according  
5 to same procedure as indicated in Example 6.

The catalyst used in this test was the  
GaNd(0.4)-ZSM-5 zeolite prepared as indicated in  
Example 2.

The reaction conditions during the test were  
10 the following:

Reaction temperature : 350-475°C

Pressure : 5 barg

WHSV : 1 g/g/hr

[1-pentene]/[n-pentane] : 60:40 w/w

15 3 g of catalyst were introduced in the reactor  
(the catalyst being obtained by tabletting the  
powdered GaNd(0.4)-ZSM-5 zeolite of Example 2 at a  
pressure of 10 ton/cm<sup>2</sup>, and by grinding it and  
sifting it in granules having a size of 20-40 mesh)  
20 between two layers of inert material (corindone).

The catalytic bed had a depth of 3-4 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

Table 7 gives the results of the test,  
5 expressed in a similar way as in Table 1.

**Table 7**

Time on stream (hours)	24.5	48.5	72.5	96.5	132.3	139.3
WHSV (hours <sup>-1</sup> )	1	1	1	1	1	1
Temperature (°C)	350	375	400	425	450	475
Conversion of 1-pentene (%)	99.9	99.9	99.9	99.9	99.9	99.9
Conversion of pentane (%)	81.3	93.4	93.1	97.2	94.5	90.0
BTEX (wt% over total)	21.8	30.1	27.2	39.7	29.8	25.8
Total aromatic compounds (wt%)	31.1	42.0	35.2	48.1	35.6	31.5
Total olefins (wt%)	1.4	0.6	0.9	0.7	1.7	2.3
Total paraffins (wt%)	51.0	47.0	53.5	41.4	54.6	53.8
Total naphthalenes (wt%)	3.8	2.2	4.0	4.6	2.7	5.5
BTEX productivity (kg/kg)	9.0	18.5	26.7	38.2	51.3	52.7

Example 13

Preparation of GaLa(0.4)-ZSM-5

A catalyst having a lanthanum content of 0.4  
10 wt% was prepared starting from 8 g of the foregoing  
specimen of Example 1 (Ga-ZSM-5) by means of

impregnation with 12 ml of an aqueous solution of La(NO<sub>3</sub>)<sub>3</sub>.6H<sub>2</sub>O (0.015 M). The catalyst was subsequently dried at 120°C and calcined in air at 550°C for 5 hours. The specimen is referred to as 5 GaLa (0.4)-ZSM-5.

Example 14

Aromatization test of 1-pentene/n-pentane with  
GaLa(0.4)-ZSM-5

The aromatization test was conducted according 10 to same procedure as indicated in Example 6.

The catalyst used in this test was the GaLa(0.4)-ZSM-5 zeolite prepared as indicated in Example 13.

The reaction conditions during the test were 15 the following:

Reaction temperature : 425-500°C

Pressure : 5 barg

WHSV : 1 g/g/hr

[1-pentene]/[n-pentane] : 60:40 w/w

20 3 g of catalyst were introduced in the reactor (the catalyst being obtained by tabletting the powdered GaLa(0.4)-ZSM-5 zeolite of Example 13 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and sifting it in granules having a size of 20-40 mesh) 25 between two layers of inert material (corindone).

The catalytic bed had a depth of 3-4 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

Table 8 gives the results of the test,  
5 expressed in a similar way as in Table 1.

**Table 8**

Time on stream (hours)	24.5	48.5	72.5	96.5
WHSV (hours <sup>-1</sup> )	1.25	1.25	1.25	1.25
Temperature (°C)	425	450	475	500
Conversion of 1-pentene (%)	99.9	99.9	99.9	99.9
Conversion of pentane (%)	90.1	85.4	95.5	96.3
BTEX (wt% over total)	33.2	44.8	48.5	50.7
Total aromatic compounds (wt%)	39.7	52.5	54.0	54.8
Total olefins (wt%)	2.7	0.7	0.4	0.6
Total paraffins (wt%)	41.0	19.2	30.2	25.1
Total naphthalenes (wt%)	8.0	16.0	9.1	13.4
BTEX productivity (kg/kg)	13.8	26.6	40.8	55.8

Example 15

Aromatization test of 1-pentene/n-pentane with  
GaNd (0.4)-ZSM-5

10 The aromatization test was conducted according to same procedure as indicated in Example 6.

The catalyst used in this test was the

GaNd(0.4)-ZSM-5 zeolite prepared as indicated in Example 2.

The reaction conditions during the test were the following:

5 Reaction temperature : 425-500°C  
Pressure : 5 barg  
WHSV : 1 g/g/hr  
[1-pentene]/[n-pentane] : 60:40 w/w

3 g of catalyst were introduced in the reactor  
10 (the catalyst being obtained by tabletting the powdered GaNd(0.4)-ZSM-5 zeolite of Example 2 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and sifting it in granules having a size of 20-40 mesh) between two layers of inert material (corindone).  
15 The catalytic bed had a depth of 3-4 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

Table 9 gives the results of the test conducted using the catalyst and the procedure  
20 specified in Example 15.

Table 9

Time on stream (hours)	24.5	72.5	96.5	102.5
WHSV (hours <sup>-1</sup> )	1.25	1.25	1.25	1.25
Temperature (°C)	425	450	475	500

Conversion of 1-pentene (%)	99.9	99.9	99.9	99.9
Conversion of pentane (%)	98.9	99.5	99.4	98.3
BTEX (wt% over total)	40.7	43.8	43.4	42.4
Total aromatic compounds (wt%)	47.2	49.4	48.0	46.4
Total olefins (wt%)	0.3	0.4	0.5	0.6
Total paraffins (wt%)	42.1	39.4	41.4	46.4
Total naphthalenes (wt%)	6.3	6.6	6.7	9.2
BTEX productivity (kg/kg)	10.8	37.8	51.1	54.3

Example 16

Preparation of GaNd(0.4)Re-ZSM-5

A catalyst having a neodymium content of 0.4 wt% and a rhenium content of 0.5 wt% was prepared starting from 13 g of the foregoing specimen of Example 2 (GaNd(0.4)-ZSM-5) by means of impregnation with 15 ml of an aqueous solution of ReCl<sub>3</sub> (0.023 M). The catalyst was subsequently dried at 110°C and calcined in air at 550°C for 5 hours. The specimen is referred to as GaNd(0.4)Re-ZSM-5.

Example 17

Aromatization test of 1-pentene/n-pentane with GaNd(0.4)Re-ZSM-5

The aromatization test was conducted according to same procedure as indicated in Example 6.

The catalyst used in this test was the GaNd(0.4)Re-ZSM-5 zeolite prepared as indicated in Example 16.

The reaction conditions during the test were  
5 the following:

Reaction temperature : 425-500°C

Pressure : 5 barg

WHSV : 1.25 g/g/hr

[1-pentene]/[n-pentane] : 60:40 w/w

10 3 g of catalyst were introduced in the reactor (the catalyst being obtained by tabletting the powdered GaNd(0.4)Re-ZSM-5 zeolite of Example 16 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and sifting it in granules having a size of 20-40 mesh)  
15 between two layers of inert material (corindone). The catalytic bed had a depth of 3-4 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

Table 10 gives the results of the test  
20 conducted using the catalyst and the procedure specified in Example 17.

**Table 10**

Time on stream (h)	24.5	72.5	114.0	138.0
WHSV (hours <sup>-1</sup> )	1.25	1.25	1.25	1.25

Temperature (°C)	425	450	475	500
Conversion of 1-pentene (%)	99.9	99.9	99.9	99.9
Conversion of pentane (%)	96.4	99.0	95.7	96.3
BTEX (wt % over total)	46.7	47.7	47.7	49.1
Total aromatic compounds (wt %)	53.8	54.0	52.0	52.8
Total olefins (wt %)	0.4	0.2	0.6	1.1
Total paraffins (wt %)	31.0	32.5	35.0	35.1
Total naphthalenes (wt %)	8.4	8.0	6.6	5.5
BTEX productivity (kg/kg)	14.4	40.9	63.0	77.8

Example 18

Preparation of GaTR(0.4)-ZSM-5

A catalyst having a rare-earth content of 0.4 wt% was prepared starting from 10 g of the foregoing specimen of Example 1 (Ga-ZSM-5) by means of impregnation with 15 ml of an aqueous solution containing 0.1 g of a mixture of carbonates of rare earths and 0.2 cc of HNO<sub>3</sub>. The mixture of carbonates of rare earths comprised the following compounds: La (37.2 wt%), Nd (10.8 wt%) Ce (7.3 wt%), and Pr (4.5 wt%). The catalyst was subsequently dried at 110°C and calcined in air at 550°C for 5 hours. The specimen is referred to as GaTR(0.4)-ZSM-5.

Example 19

Aromatization test of 1-pentene/n-pentane with  
GaTR(0.4)-ZSM-5 (1-pentene 60 wt%)

The aromatization test was conducted according  
5 to same procedure as indicated in Example 6.

The catalyst used in this test was the  
GaTR(0.4)-ZSM-5 zeolite prepared as indicated in  
Example 18.

The reaction conditions during the test were  
10 the following:

Reaction temperature : 425-500°C

Pressure : 5 barg

WHSV : 1.25 g/g/hr

[1-pentene]/[n-pentane] : 60:40 w/w

15 3 g of catalyst were introduced in the reactor  
(the catalyst being obtained by tabletting the  
powdered GaTR(0.4)-ZSM-5 zeolite of Example 18 at a  
pressure of 10 ton/cm<sup>2</sup>, and by grinding it and  
sifting it in granules having a size of 20-40 mesh)  
20 between two layers of inert material (corindone).  
The catalytic bed had a depth of 3-4 cm. Before the  
reaction, the material was activated in a current  
of nitrogen at 400°C for 3-4 hours.

Table 11 gives the results of the test  
25 conducted using the catalyst and the procedure

specified in Example 19.

Table 11

Time on stream (h)	24.5	48.5	79.5	102.5
WHSV (hours <sup>-1</sup> )	1.25	1.25	1.25	1.25
Temperature (°C)	425	450	475	500
Conversion of 1-pentene (%)	99.9	99.9	99.9	99.9
Conversion of pentane (%)	98.3	97.6	94.3	95.6
BTEX (wt % over total)	39.0	41.0	42.0	43.8
Total aromatic compounds (wt %)	46.0	47.3	47.7	49.0
Total olefins (wt %)	0.5	0.4	1.1	1.3
Total paraffins (wt %)	36.2	36.9	37.0	36.6
Total naphthalenes (wt %)	10.3	10.1	8.0	7.7
BTEX productivity (kg/kg)	11.1	23.6	41.4	53.6

Example 20

A solution A was prepared dissolving in  
5 succession 84.4 g of  $\text{Al}_2(\text{SO}_4)_3 \cdot 16 \text{ H}_2\text{O}$ , 327.6 g of  
tetrapropyl ammonium bromide, and 984.0 g of sodium  
chloride in 3096.0 g of water; next, 220.0 g of 96  
wt% sulphuric acid were added. A solution B was  
prepared, made up of 2808 g of sodium silicate (27  
10 wt%  $\text{SiO}_2$ , 8 wt%  $\text{Na}_2\text{O}$ ) and 4480 g of water.

The solution B was introduced in a 20-litre

autoclave, and the solution A was added under vigorous stirring. The final mixture obtained was crystallized at autogenous pressure, at a temperature of 100°C for 10 days, stirring at a 5 peripheral speed of 65 m/min.

After this period, the autoclave was cooled, the crystallization slurry was discharged, the solid phase was separated, washed by re-dispersion in water, and calcined at 550°C for 5 hours. Next, 10 the specimen was exchanged into acid form by treatment with ammonium acetate. The specimen thus obtained was characterized by a final SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> molar ratio of 76.5.

At XRD analysis, the product was found to 15 consist of pure MFI, characterized by the following cell parameters: a = 20.1241(27) Å, b = 19.9184(24) Å, c = 13.4035(17) Å, V = 5372.7(28) Å<sup>3</sup>, mean size of the crystallites according to Scherrer's equation = 280 Å in diameter. At TEM 20 analysis, the zeolitic phase appeared in the form of relatively dense, mulberry-shaped submicron aggregates, which in turn consisted of regularly sized crystallites having diameters ranging from 200 to 500 Å. Figure 1 presents a TEM micrograph of 25 the specimen (enlargement 40000x). The specimen was

characterized by means of mercury-intrusion porosimetry up to a pressure of 2000 bar: in the pressure range considered this analysis enables determination of the distribution of the pores with 5 radiiuses greater than 37 Å. The specimen was found to possess an extrazeolitic porosity of a substantially meso-macroporous nature, presenting 60.3 % of the volume of the pores in the mesoporous region (diameter < 500 Å). 90% of the porosity was 10 between 37 and 1000 Å in radius, with a mean diameter of 480 Å.

Example 21

20 g of zeolite obtained in foregoing example 15 were impregnated with an aqueous solution first of  $\text{Ga}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$  (20 ml, 0.43 M) and subsequently of  $\text{Nd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$  (20 ml, 0.023 M). Between the two impregnations the catalyst was subjected to drying (in air at 120°C). At the end of the operations, 20 the specimen was subsequently dried at 120°C and calcined in air at 550°C for 5 hours. The specimen thus obtained was characterized by a final  $\text{SiO}_2/\text{Al}_2\text{O}_3$  molar ratio of 76.5, a final Ga content of 3.17 wt% and a final Nd content of 0.31 wt%.

25           Example 22

Example 20 was repeated using 99.6 g of  $\text{Al}_2(\text{SO}_4)_3 \cdot 16\text{H}_2\text{O}$  and 213.3 g of  $\text{H}_2\text{SO}_4$  (96 wt%). The final specimen exchanged into acid form was characterized by a  $\text{SiO}_2/\text{Al}_2\text{O}_3$  molar ratio of 65.8.

At XRD analysis the product was found to consist of pure MFI, characterized by the following cell parameters:  $a = 20.1232(29)$  Å,  $b = 19.9155(26)$  Å,  $c = 13.40045(18)$  Å,  $V = 5370.4(29)$  Å<sup>3</sup>, mean size of the crystallites according to Scherrer's equation = 245 Å in diameter. At TEM analysis, the zeolitic phase appeared in the form of relatively dense, mulberry-shaped submicron aggregates, which in turn consisted of regularly sized crystallites having diameters within the 200-500 Å range.

#### Example 23

20 g of zeolite obtained according to the foregoing example were treated as described in Example 21, using an aqueous solution first of  $\text{Ga}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$  (40 ml, 0.22 M) and subsequently of  $\text{Nd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$  (38 ml, 0.013 M). A catalyst was obtained with a final Ga content of 2.73 wt% and Nd content of 0.44 wt%.

#### Example 24

For this example, a commercially available

ZSM-5 zeolite (PQ Zeolites, CBV 3020) was used, already exchanged into acid form, consisting of crystallites having a wide diameter distribution of between 100 and 1000 Å, and a mean diameter, 5 estimated by means of Scherrer's equation, of 505 Å. A specimen of this zeolite was characterized by means of mercury-intrusion porosimetry up to a pressure of 2000 bar. The specimen was found to possess substantially an extrazeolitic porosity 10 distributed in the macroporosity range, only 8.5 % of the porous volume being included in the mesoporosity region (diameter < 500 Å). The mean diameter of the pores was 1790 Å. Figure 2 presents the TEM micrograph of the specimen (enlargement 15 40000x), in which a significant presence of crystallites of diameter greater than 500 Å may be noted, as well as a wider distribution of the diameters of the crystallites as compared to the specimen of Example 20 (Fig. 1).

20 g of the zeolite described above were impregnated with an aqueous solution first of  $\text{Ga}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$  (20 ml, 0.43 M) and subsequently of  $\text{Nd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$  (20 ml, 0.023 M). Between the two impregnations, the catalyst was subjected to drying 25 (in air at 120°C). At the end of the operations,

the specimen was subsequently dried at 120°C and calcined in air at 550°C for 5 hours. The resulting specimen was characterized by a final SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> molar ratio of 32.1, a final Ga content of 2.96 wt%, and a final Nd content of 0.23 wt%.

Example 25

Aromatization test at constant temperature of  
1-pentene / n-pentane

An aromatization test of a charge of C<sub>5</sub> hydrocarbons (made up of 1-pentene and n-pentane in a weight ratio of 60:40) was conducted using an experimental apparatus consisting of a steel reactor (length = 710 mm, internal diameter = 12.5 mm, external diameter = 35 mm) equipped with an internal thermometric sheath for control of the temperature. Heating took place with the aid of 4 ovens arranged in series along the reactor itself. The catalyst was introduced in the form of granules of appropriate sizes (20-40 mesh) and diluted with inert material (corindone). The feeding of the reagents (contained in a special refrigerated tank and kept under pressure in nitrogen) was performed using an HPLC pump. The products coming out of the reactor were condensed (at a temperature of 5 °C) and collected, partly in the liquid phase, and

partly in the gas phase. Both the phases then underwent gas-chromatography analysis.

The catalyst used in this test was the one prepared according to Example 21.

5       The reaction conditions during the test were the following:

Reaction temperature : 450°C

Pressure : 5.7 barg

WHSV : 1.25 g/g/hr

10      [1-pentene]/[n-pentane] : 60:40 w/w

3.07 g of catalyst were introduced in the reactor (the catalyst being obtained by tabletting the powdered catalytic composition of Example 21 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and 15 sifting it in granules having a size of 20-40 mesh) between two layers of inert material (corindone). The catalytic bed had a depth of 2-3 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

20      Figure 3 gives the BTEX (benzene, toluene, ethylbenzene and xylene) yield values (wt% over total of the effluents of the reactor) that were obtained in the course of the test as the time on stream (t.o.s., hours) varied.

25      Example 26

Aromatization test at constant temperature of  
1-pentene / n-pentane

The aromatization test was conducted according to the same procedure as the one indicated in 5 Example 25.

The catalyst used in this test is the catalytic composition prepared according to Example 21.

The reaction conditions during the test were 10 the following:

Reaction temperature : 500°C (constant throughout the test)

Pressure : 5.7 barg

WHSV : 1.25 g/g/hr

15 [1-pentene]/[n-pentane] : 60:40 w/w

3.07 g of catalyst were introduced in the reactor (the catalyst being obtained by tabletting the powdered catalytic composition of Example 21 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and 20 sifting it in granules having a size of 20-40 mesh) between two layers of inert material (corindone). The catalytic bed had a depth of 2-3 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

25 Figure 4 gives the BTEX yield values (wt% over

total of the effluents of the reactor) that were obtained in the course of the test as the time on stream (t.o.s., hours) varied.

Example 27

5           Aromatization test at constant temperature and  
high WHSV of 1-pentene / *n*-pentane

The aromatization test was conducted according to the same procedure as the one indicated in Example 25.

10 In order to assess the performance of the catalyst in conditions of greater stress, the test was carried out at a WHSV value four times the value adopted in the foregoing examples.

The catalyst used in this test is the  
15 catalytic composition prepared according to Example  
21.

The reaction conditions during the test were the following:

Reaction temperature : 500°C (constant throughout the test)

Pressure : 5.7 barg

Pressure : 5.7 barg

WHSV : 4 g/g/m<sup>2</sup>

[1-pentene] / [n-pentane] : 60:40 w/w

3.10 g of catalyst were introduced in the  
25 reactor (the catalyst being obtained by tabletting

the powdered catalytic composition of Example 21 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and sifting it in granules having a size of 20-40 mesh) between two layers of inert material (corindone).

5 The catalytic bed had a depth of 2-3 cm. Before the reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

Figure 5 gives the BTEX yield values (wt% over total of the effluents of the reactor) that were 10 obtained in the course of the test as the time on stream (t.o.s., hours) varied. (Line ■).

Example 28

Aromatization test at constant temperature and high WHSV of 1-pentene / n-pentane

15 The aromatization test was conducted according to the same procedure as the one indicated in Example 27.

The catalyst used in this test is the catalytic composition prepared according to Example 20 24.

The reaction conditions during the test were the following:

Reaction temperature : 500°C (constant throughout the test)

25 Pressure : 5.7 barg

WHSV : 4 g/g/hr

[1-pentene]/[n-pentane] : 60:40 w/w

3.10 g of catalyst were introduced in the reactor (the catalyst being obtained by tabletting 5 the powdered catalytic composition of Example 24 at a pressure of 10 ton/cm<sup>2</sup>, and by grinding it and sifting it in granules having a size of 20-40 mesh) between two layers of inert material (corindone). The catalytic bed had a depth of 2-3 cm. Before the 10 reaction, the material was activated in a current of nitrogen at 400°C for 3-4 hours.

Figure 5 gives the BTEX yield values (wt% over total of the effluents of the reactor) that were obtained in the course of the test as the time on stream (t.o.s., hours) varied. (Line ▲).

An examination of the data of BTEX yield (wt% over total of the effluents of the reactor) given in Figure 5, obtained from the aromatization tests conducted at T = 500°C and WHSV = 4 h<sup>-1</sup> described 20 in Examples 27 and 28, reveals how the catalytic performance of the catalyst of Example 21 and of the catalyst of Example 24 are similar for t.o.s. values smaller than 50 hours, whilst they differ for t.o.s. values greater than 50 hours.

25 Example 29

Aromatization tests at variable temperature of  
1-pentene / n-pentane

With the purpose of maximizing the performance of the catalyst, it is a consolidated procedure to increase the temperature in the course of time. The ensuing Table 12 gives the data referring to two distinct tests, which were conducted according to the operating procedure described in Example 25, using the catalysts prepared according to Examples 23 and 24. In the course of these tests, the temperature T (expressed in °C) was increased at the end of time intervals  $\Delta t$  (in hours) set in an identical manner for each of the two catalysts.

Note that for equal t.o.s. values, at all the reaction temperatures considered the catalyst of Example 23 presents higher BTEXT yield values, as compared with the catalyst of Example 24.

Table 12

		Catalyst	
		Example 24	Example 23
$\Delta t$ [hours]	T [ $^{\circ}$ C]	BTEX yield (wt% over total)	BTEX yield (wt% over total)
0-50	425	48	52
50-80	450	49	56
80-100	475	48.5	58
100-140	500	45	59
140-160	525	21	60
160-180	550	-	59
180-200	575	-	35

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